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**Raytheon**

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**Air Traffic Management System  
Development and Integration  
(ATMSDI)**

**CTOD-2.3-2**

**Draft Guidelines**

**Subtask 2 – Human Error Prediction and  
Amelioration**

**December 2001**

**Contract No.: NAS2-00015**

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## **ACKNOWLEDGEMENT**

The authors sincerely thank Dr. Richard Mogford for providing ideas and literature, and encouraging discussions.

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## **EXECUTIVE SUMMARY**

Examination of human error potential in the future air traffic management concepts is an important aspect of feasibility assessments. There are a number of techniques that address human error potential. However, to date there are no clear guidelines related to how the potential for human error needs to be identified for future air traffic management concepts. This initial guidelines document describes a process for identification and mitigation of human errors within the Distributed Air-Ground Traffic Management domain. These guidelines will be updated as further understanding and information becomes available.

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## 1. BACKGROUND

Distributed Air-Ground Traffic Management (DAG-TM) represents a paradigm shift where the roles and responsibilities of air traffic service provider (ATSP), traffic flow management (TFM) specialists (TFMS), flight crew (FC), and airline operations center specialists (AOCS) will change. These new roles and responsibilities will require different decision support tools and procedures. These changes may alter the human tasks and allocation of functions between humans as well as between the human and the machine. Therefore, it is imperative to examine the potential error modes and potential error mitigation strategies under such conditions.

This document presents guidelines for the assessment of human error and the error mitigation process for DAG-TM concepts.

## 2. OBJECTIVE

The objective of this initial guidelines document is to describe a process that can be adopted for human error assessment and mitigation for the DAG-TM operations. The primary focus of the guidelines is on the prospective (or predictive) human error assessment to identify potential errors in DAG-TM and their implications of these errors on system design.

The objectives of these guidelines are as follows:

- Provide guidance on human error prediction methods to assess the benefits and safety of DAG-TM concepts,
- Provide guidance to system designers regarding error tolerant systems development,
- Identify error elimination, reduction, and mitigation strategies (with decision support tools, procedures), and
- Ensure that human error potential is controlled within new concepts.

The authors examined a range of human error assessment techniques for their strengths, weaknesses, and applicability and provided recommendations for their suitability for DAG-TM applications.

## 3. SCOPE

The scope of these guidelines includes identification of suitable human error assessment techniques for anticipating human error in new air traffic management (ATM) systems and their impact on error mitigation strategies. These guidelines particularly focus on concept element (CE) 5: En Route Free Maneuvering and CE 11: Terminal Self-Spacing for In-trail and Merging.

These initial guidelines will be updated in fiscal year 2002 based on any additional available information related to DAG-TM validation studies.

Sections 4 and 5 describe DAG-TM CE 5 (En Route Free Maneuvering) and CE 11 (Terminal Self-spacing), respectively. These descriptions are taken from the DAG-TM concept definition documents developed by NASA Ames Research Center (NASA AATT, 1999).

## 4. DESCRIPTION OF CE 5: EN ROUTE: FREE MANEUVERING FOR USER-PREFERRED SEPARATION ASSURANCE AND LOCAL TFM CONFORMANCE

It is noted that this concept element applies to all flight phases (Departure, Cruise and Arrival) in the operational domain of en route airspace.

### 4.1 CURRENT PROBLEM

**(a) ATSP often responds to potential traffic separation conflicts by issuing trajectory deviations that are excessive or not preferred by users.**

In the current air traffic control (ATC) system, trajectory prediction uncertainty leads to excessive ATC deviations for separation assurance. Due to workload limitations, controllers often compensate for this uncertainty (which may be equivalent to or greater than the minimum separation standard) by adding large separation buffers for conflict detection and resolution (CD&R). Although these buffers reduce the rate of missed alerts, some aircraft experience unnecessary deviations from their preferred trajectories due to the unnecessary “resolution” of false alarms (i.e., predicted “conflicts” that would not have materialized had the aircraft continued along their original trajectories). In those cases where a potential conflict really does exist, the buffers lead to conservative resolution maneuvers that result in excessive deviations from the original trajectory. Moreover, the nature of the resolution (change in route, altitude or speed) may not be user-preferred. Due to a lack of adequate traffic, weather, and airspace restriction information (and the means to present such information), and also a lack of conflict resolution tools on the flight deck, current procedures generally do not permit the user to effectively influence controller decisions for conflict resolution.

**(b) ATSP often cannot accommodate the user’s trajectory preferences for conformance with local TFM constraints.**

The dynamic nature of both aircraft operations and NAS operational constraints often result in a need to change a 4-D trajectory plan while the aircraft is en route. Currently, the user (FC or AOC) is required to submit a request for a trajectory change to the ATSP for approval. During flow-rate constrained operations, the ATSP is rarely able to consider user preferences for conformance. Additionally, a lack of accurate information on local traffic and/or active local TFM constraints (bad weather, special use airspace (SUA), airspace congestion, arrival metering/spacing) can result in the FC or AOC requesting an unacceptable trajectory. The ATSP is forced to plan and implement clearances that meet separation and local TFM constraints, but may not meet user preferences. Further negotiation between the ATSP and FC can adversely impact voice-communication channels and increase ATSP and FC workload.



## 4.2 SOLUTION (FLIGHT DECK FOCUS)

- (a, b) Appropriately equipped aircraft accept the responsibility to maintain separation from other aircraft, while exercising the authority to freely maneuver in en route airspace in order to establish a new user-preferred trajectory that conforms to any active local TFM constraints.**

While in the en route operational domain, appropriately equipped aircraft are given the authority, capability and procedures needed to execute user-preferred trajectory changes without requesting ATSP clearance to do so. Along with this authority, the flight crew takes on the responsibility to ensure that the trajectory change does not generate near-term conflicts with other aircraft in the vicinity. The trajectory change should also conform to any active local TFM constraints (e.g., bad weather, SUA, airspace congestion, arrival metering/spacing). User-preferred trajectory modification may be generated by the FC with AOC input if appropriate, or generated entirely by the AOC and transmitted to the FC via datalink. The FC broadcasts its modified flight plan via datalink (includes notification of ATSP) immediately after initiation of trajectory modification; in most situations, this task is handled by on-board automation.

The ATSP monitors separation conformance for free maneuvering aircraft, and provides separation assurance for lesser-equipped aircraft using CD&R decision support tools (DSTs). The ATSP may act on behalf of lesser-equipped aircraft when they are in potential conflict with free maneuvering aircraft. For cases where the flight crew attempts, and fails, to resolve a conflict, automated systems or the ATSP will provide a required resolution. Procedures and flight rules are established that provide incentive for aircraft to equip for self-separation, such as, perhaps, priority status in conflicts with lesser-equipped aircraft.

## 4.3 POTENTIAL BENEFITS OF THE CE 5 OPERATION:

- Reduction in excessive and non-preferred deviations for separation assurance and local TFM conformance, due to the ability of the flight crew (for equipped aircraft) to self-separate and maintain local TFM conformance according to their preferences.
- Increased safety in separation assurance for all aircraft, due to communications, navigation, and surveillance redundancy (FC as primary and ATC as backup) and increased situational awareness of the FC of appropriately equipped aircraft.
- Reduced ATSP workload for separation assurance and local TFM conformance plus reduced FC workload for communications, due to the distribution of responsibility for separation assurance and local TFM conformance between the ATSP and appropriately equipped FCs.

A detailed description of CE 5 can be found in Philips (2000).

## 5. DESCRIPTION OF CE 11: TERMINAL ARRIVAL: SELF-SPACING FOR MERGING AND IN-TRAIL SEPARATION

### 5.1 CURRENT PROBLEM

- (a) Excessive in trail spacing buffers in arrival streams reduce runway throughput and airport capacity, especially in conditions of poor visibility and /or low ceilings.**

In terminal area environments for which arrival demand approaches or exceeds capacity, aircraft landing rates are significantly lower under instrument meteorological conditions (IMC) than under visual meteorological conditions (VMC). In order to compensate for uncertainties in aircraft performance and position, the ATSP applies in-trail spacing buffers to arrival streams under IMC in order to ensure that minimum separation requirements between successive aircraft are met. The resulting generous arrival spacing reduces runway throughput below its capacity to accept aircraft.

### 5.2 SOLUTION (FLIGHT DECK FOCUS)

Appropriately equipped aircraft are given a clearance to merge with another arrival stream, and/or maintain in-trail separation relative to a leading aircraft.

In VMC, aircraft are often able to maintain closer spacing during the approach, thereby increasing the capacity of the terminal area and the runway acceptance rate. In the current system, the FC is often requested to accept responsibility for visual self-separation once they acknowledge they can see the leading aircraft. In this situation, the FC is responsible for determining and then maintaining a safe separation from other aircraft, and is therefore not subject to the ATSP minimum separation requirements.

Self-spacing operations will enable the FC to autonomously merge with another arrival stream and/or maintain in-trail separation with another aircraft under IMC as they would under VMC, thus significantly increasing arrival throughput. Self-spacing applies to aircraft that are subject to spacing requirements during arrival, from the feeder fix, up to the final approach fix.

Anticipated procedures for self-spacing involve the ATSP transferring responsibility for in-trail separation to properly equipped aircraft, while retaining responsibility for separating these aircraft from crossing traffic. Once the FC receives clearance to maintain spacing relative to a designated leading aircraft, the FC establishes and maintains a relative position with frequent monitoring and speed/course adjustments. Under some conditions, information such as required time of arrival at the final approach fix may be provided by an appropriate ATSP-based DST, thereby enabling accurate inter-arrival spacing that accounts for differing final approach speeds or wake vortex avoidance. ATSP monitors all aircraft to ensure adequate separation. For cases where the flight crew fails to maintain adequate spacing, automated systems or the ATSP will provide a required correction.

The self-spacing concept is expected to make use of datalink capabilities to provide position information and a cockpit display of traffic information and/or advanced flight director/head-up guidance technology to provide spatial and temporal situation awareness to the flight crew. FC-based DSTs will provide information to enable station-keeping and/or monitoring of automatic 4-D trajectory management.

A detailed description of CE 11 can be found in Sorensen (2000).

### **5.3 POTENTIAL BENEFITS OF THE CE 11 OPERATION**

- Increased arrival capacity/throughput in IMC, due to a reduction in excessive spacing buffers resulting from the ability of appropriately equipped aircraft to operate as if they were in VMC.
- Reduced ATSP workload, due to transfer of separation responsibility to the flight crew of appropriately equipped aircraft.

## **6. GUIDELINES FOR CONDUCTING PROSPECTIVE HUMAN ERROR ASSESSMENTS**

The following guidelines describe a process for conducting prospective human error assessment and their implications on the design of DSTs and procedures related to CE 5 and CE 11. These guidelines are primarily meant for the DAG-TM researchers but would be useful for system designers, subject matter experts (SMEs), sponsors, academic researchers, and managers. FY01 guidelines are focused on identifying the process of human error assessment. The system designers will find these guidelines useful in the development of error tolerant systems to ensure that the error potential and effects are controlled within the DAG-TM operation.

These guidelines were developed based on the literature review (Kopardekar, 2001), discussions with SMEs, and the authors' experience. These guidelines present best practices in error identification and identify design characteristics that will eliminate or mitigate the impact of these errors.

While identifying the error assessment process, the following characteristics were considered:

- The error assessment method must be based on a detailed task analysis (Kirwan, 1994),
- While comparing error potential of multiple functional allocation schemes, it should consider relative judgment of error potential (rather than absolute judgment) for higher accuracy (Swain and Guttman, 1993),
- The method should accommodate tasks from multiple agents: pilots, controllers, traffic flow managers, and dispatchers,
- It should consider input from multiple participants and not from only one expert; and
- It should trace system characteristics to the cause of the error in order to mitigate the error potential.

In addition to the authors' own ideas, the elements of the following techniques were used in developing these guidelines:

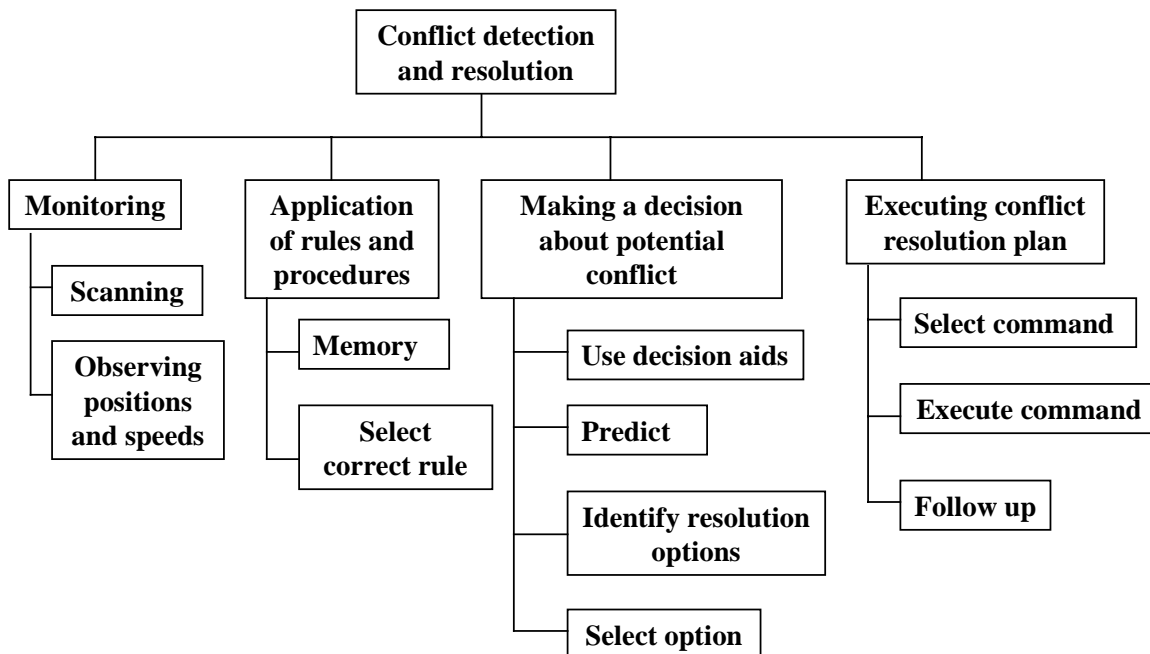
- Theoretical taxonomies (e.g., by Rasmussen, 1982),
- FAA's Human Factors Analysis and Classification Scheme (HFACS),

- Eurocontrol's Human Error Reduction in ATM (HERA),
- FAA and Eurocontrol's joint harmonized model (as part of Action Plan 12) JANUS,
- United Kingdom's National Air Traffic Service developed technique called Technique for Retrospective Analysis of Cognitive Error (TRACER),
- Analytic Hierarchy Process (AHP) for comparing error potential among multiple functional decomposition schemes or comparing error potential between a baseline and a proposed CE,
- Quality Function Deployment (QFD)/House of Quality method to trace the error causes to mitigation strategies as described by system characteristics, and
- Fault-tree and event-tree analysis.

The following is a step-by-step process for conducting prospective human error assessment.

**Step 1: Conduct task analysis of CE 5 and CE 11 and identify potential functional allocation schemes (this task analysis can be extended to CE 6 and CE 7 since they are also en route concepts).**

In the first step, a detailed task analysis of FC, ATSP, and AOCS is conducted for each CE under consideration. This detailed task analysis serves as an initial but crucial step for error analysis. The task analysis provided by Rodgers and Drechsler (1993, 1995) will be used as a starting point. Figure 1 depicts a task analysis.



**Figure 1. Example Task Analysis of Conflict Detection and Resolution Task.**

As necessary, using the task analysis the tasks will be reallocated between ATSP, FC, and AOCS based on CE descriptions and subject matter expert input.

**Step 2: Perform cognitive walkthroughs to identify potential error modes.**

In this step, a structured walkthrough will be conducted. The walkthrough will include ATSP, FC, and AOC tasks that are identified in Step 1. At each of these tasks, potential human errors will be identified. The TRACER framework will be used to categorize tasks (Shorrock & Kirwan, 2000; Shorrock, Kirwan, Isaac, Andersen, & Bove, 1999).

TRACER characterizes errors in four ways:

1. External Error Modes (EEM) classify external and observable attributes of error, such as errors of omission, errors of commission, extraneous acts.
2. Cognitive domains are stages of cognitive processing at which the error occurred (e.g., perception and vigilance, working memory, long-term memory, decision making, response selection, judgment, planning and decision-making, response execution, and signal reception).
3. Internal Error Modes (IEM) are categories of failed human information processing within cognitive domains (e.g., misjudgment, misidentification). IEMs are usually derived from incident reports.
4. Psychological Error Mechanisms (PEM) describe in detail how errors occurred in terms of psychological cause (e.g., spatial confusion, read back/hear back error) within cognitive domains.

In essence, EEM is observed error, IEM is the general human information processing stage at which the reason for the error lies, and PEM is a possible mechanism or interpretation of how errors occur. The Performance Shaping Factors provide additional contributing factors.

Table 1 provides a list of example errors.

**Table 1. Potential TRACER EEMs, IEMs, and PEMs.**

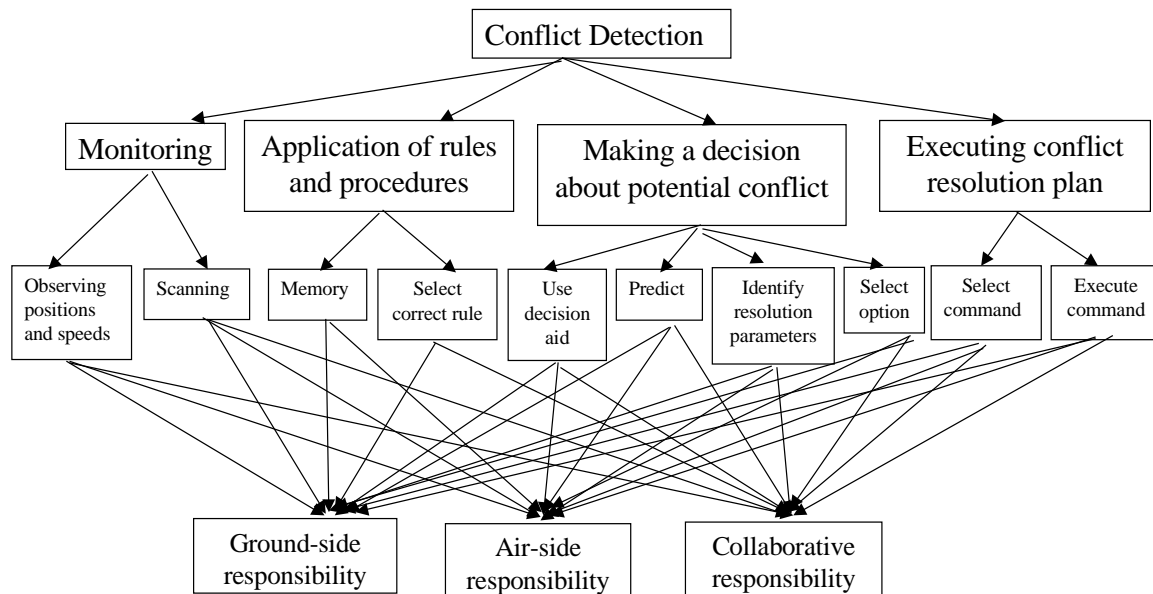
Error Mode	Description
Possible External Error Modes	<ul style="list-style-type: none"> <li>■ Omissions</li> <li>■ Commissions <ul style="list-style-type: none"> <li>– <i>Timing</i>: action too long, action too early, action too late;</li> <li>– <i>Sequence</i>: action repeated, mis-ordering;</li> <li>– <i>Quality</i>: action too much, action too little, action in wrong direction, wrong action on right object;</li> <li>– <i>Selection</i>: right action on wrong object;</li> <li>– <i>Communication errors</i>: Unclear information transmitted, unclear information recorded, information not transmitted, information not recorded, incomplete information transmitted, incomplete information recorded, incorrect information recorded, incorrect information transmitted; and</li> <li>– <i>Rule contravention</i>: unintended rule contravention, exceptional violation, routine violation, general violation.</li> </ul> </li> </ul>
Possible Internal Error Modes	<ul style="list-style-type: none"> <li>■ No detection (auditory)</li> <li>■ Late auditory recognition</li> <li>■ Hear-back error</li> <li>■ Mishear</li> <li>■ No detection (visual)</li> <li>■ No identification</li> <li>■ Misidentification</li> <li>■ Misread</li> <li>■ Visual misinterpretation</li> </ul>
Possible Psychological Error Mechanisms	<ul style="list-style-type: none"> <li>■ Expectation bias</li> <li>■ Association bias</li> <li>■ Spatial confusion</li> <li>■ Perceptual confusion</li> <li>■ Perceptual discrimination failure</li> <li>■ Perceptual tunneling</li> <li>■ Out of sight bias</li> <li>■ Stimulus overload</li> <li>■ Vigilance failure</li> <li>■ Visual search failure</li> <li>■ Monitoring failure</li> <li>■ Preoccupation</li> </ul>

The FAA and Eurocontrol are jointly developing a method to classify and analyze error in air traffic management operations. As the joint FAA/Eurocontrol error assessment technique (called JANUS) matures, we will use its taxonomy and structure for error classification.

### Step 3: Apply AHP to compare error potential of alternate concepts or with a baseline.

One of the objectives of error assessment is to compare if the new concepts reduce (or at least do not increase) error potential or to compare error potential of competing alternative functional decompositions. AHP has been used for such multi-criteria decision making applications (Saaty, 1996). It fits well with the hierarchical task analysis. The following example illustrates the use of AHP for a conflict detection and resolution task. This is a hypothetical example and is not meant to be comprehensive.

Figure 2 depicts a hierarchical task analysis that shows the three alternatives at the bottom that will be compared for error potential.



**Figure 2. AHP Structure.**

AHP typically uses a nine-point scale where the anchors mean the following:

- 1 – Equal likelihood that error will occur in one activity over another,
- 3 – Slight likelihood that error will occur in one activity over another,
- 5 – Strong likelihood that error will occur in one activity over another,
- 7 – Very strong likelihood that error will occur in one activity over another, and
- 9 – Absolute likelihood that error will occur in one activity over another.

Sample AHP calculations are shown in Appendix A. The result of the AHP method will indicate which alternative concept should be selected based on error potential.

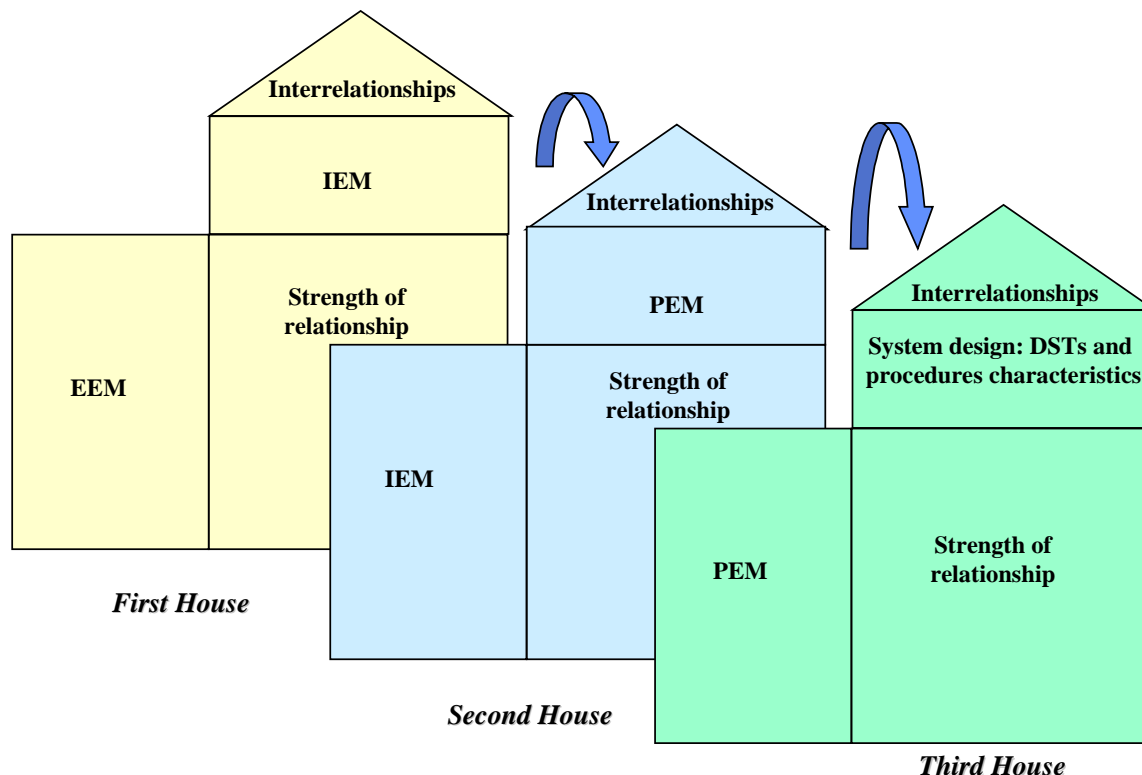
**Step 4: Apply Quality Function Deployment/House of Quality method to trace the errors to design characteristics for mitigation.**

The QFD/House of Quality approach is used to trace the customer requirements to design and process characteristics. It was originally developed for a manufacturing application. However, it has been increasingly used in service domains as well. The QFD/House of Quality structure will help determine the system characteristics that will mitigate the effects of errors that are identified in Step 2. The houses in each House of Quality are used to demonstrate the relationships (Evans & Lindsay, 1996).

The following houses will be used for error analysis (see Figure 3):

1. First House: EEMs to IEMs,
2. Second House: IEMs to PEM, and
3. Third House: PEMs to design specifications (DST and procedures) such that all PEMs are addressed by DSTs and procedures.

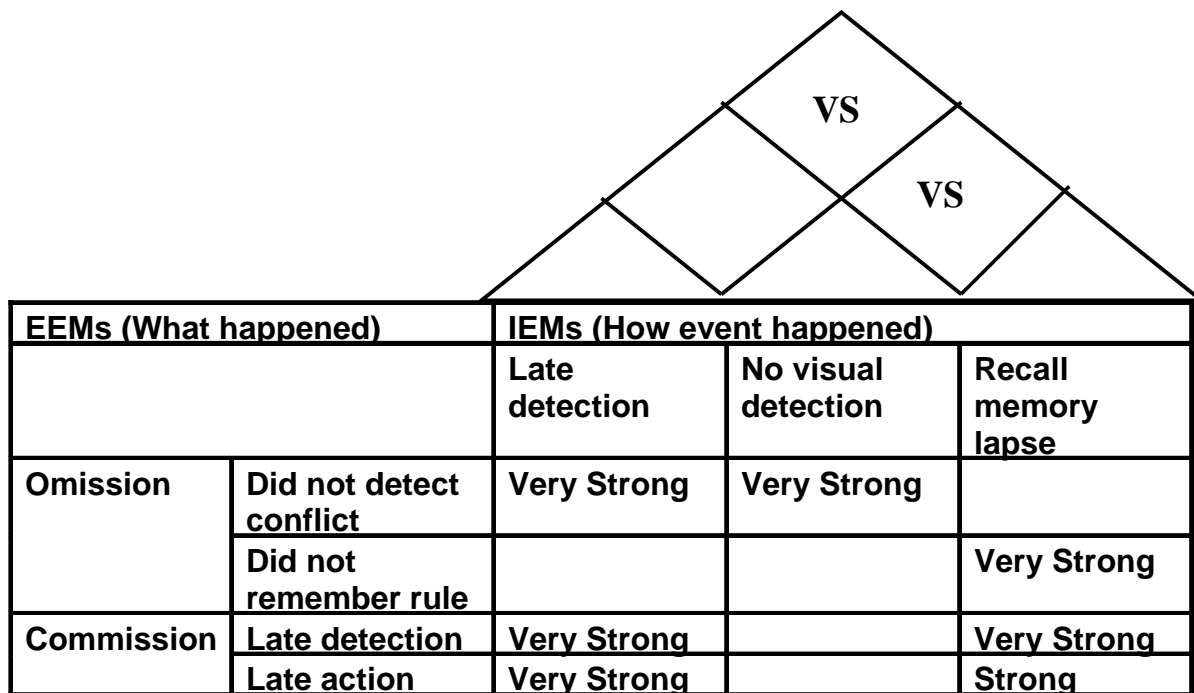
Within each house, the strength of relationships ensures that all interventions address requirements. The interrelationship between interventions will provide an idea of redundancies.



**Figure 1. QFD/House of Quality Framework.**



Figures 4, 5, and 6 describe the use of the QFD/House of Quality approach. Figure 2 describes the relationships between EEMs and IEMs in the body of the house. These relationships indicate the strength of the relationship between EEMs and IEMs. The roof of the house indicates the interrelationships between IEMs. These interrelationships are important to identify strengths of association between IEMs (e.g., VS= Very Strong, S= Strong). Figure 5 describes the relationship between IEMs and PEMs. If no relationship or a weak relationship is observed, then those PEMs can be deleted from further analysis as shown in the figure. Figure 6 depicts the relationship between PEMs and system design characteristics. The strength of relationships indicates how well the PEMs are addressed by the system design. The interrelationship on the roof indicates the association between system characteristics and helps identify redundant characteristics. The overall goal of this approach to ensure that the system design characteristics address fully the error modes and thus can mitigate the error effects.



**Figure 2. Relationship Between EEMs and IEMs.**

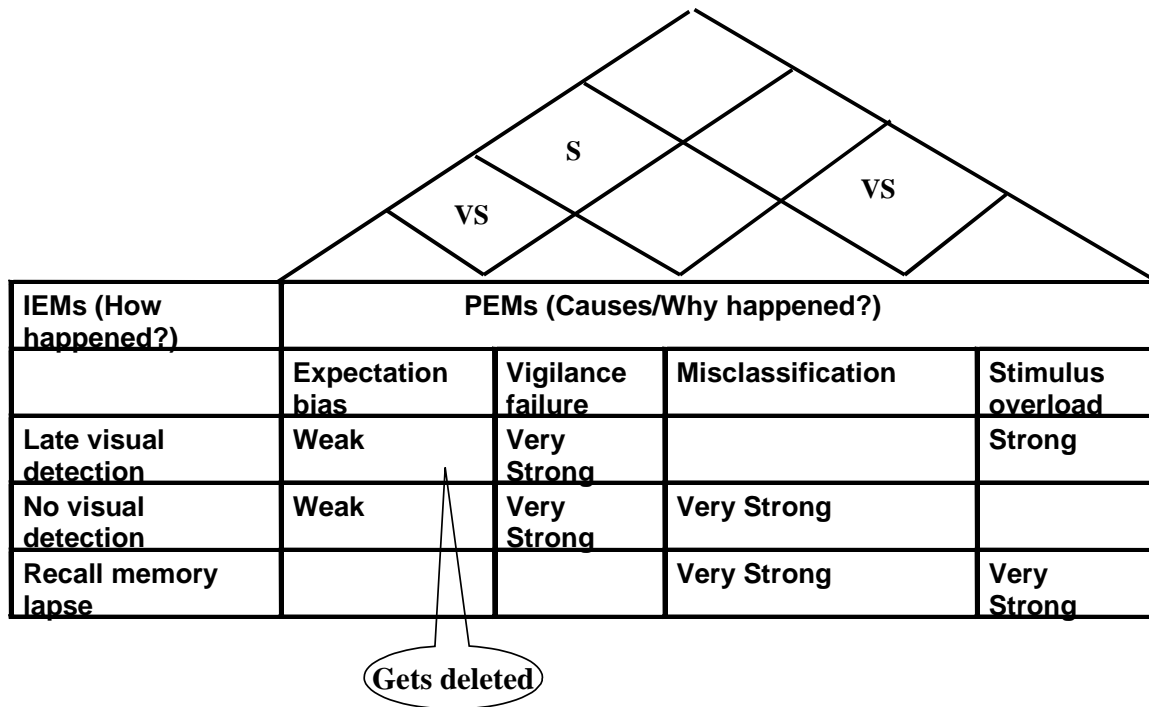


Figure 3. Relationship Between IEMs and PEMs.

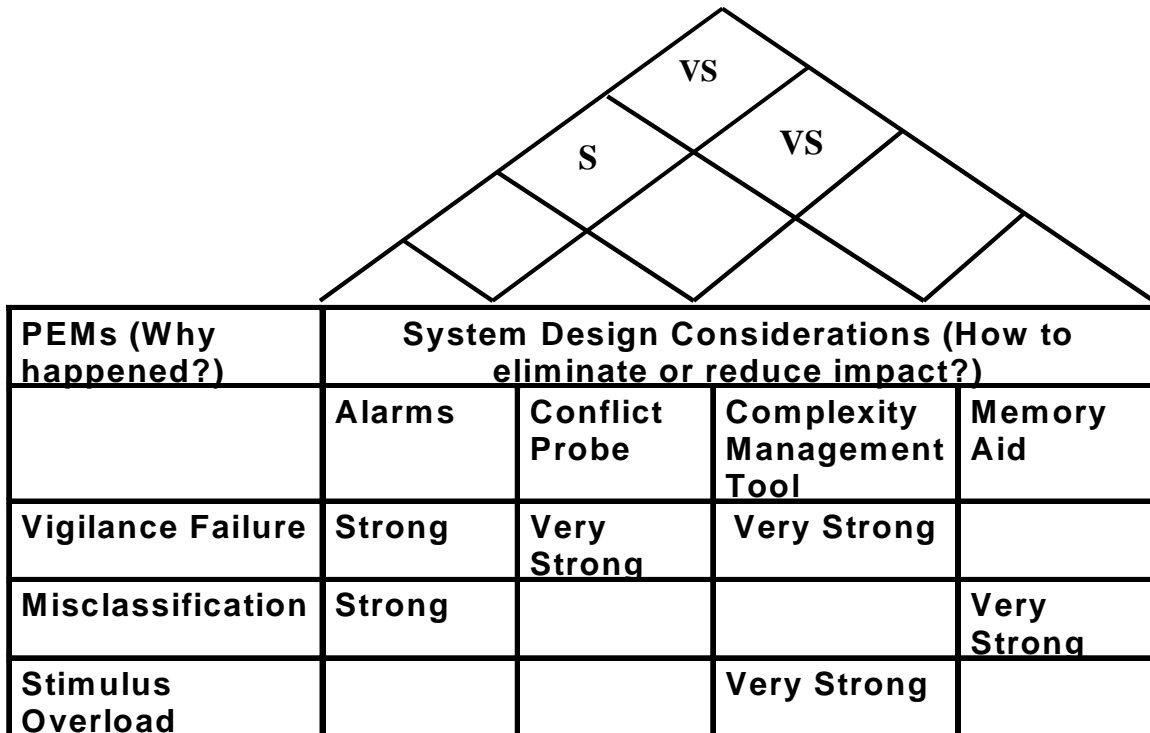


Figure 6. Relationship Between PEMs to System Design Characteristics

Step 5: Apply Decision Tree Analysis technique to ensure that critical tasks have error recovery modes and redundancies.

The last step in the analysis is to ensure that the critical tasks all have recovery modes and redundancies. The decision tree analysis process is used to make such an assessment. The objectives of this process are to:

- Ensure that error recovery is possible at critical or all tasks,
- Ensure that decision aids and procedures adequately cover the task error recovery,
- Compare to ensure that same or more recovery paths are available than baseline, and
- Compare alternate schemes.

If absolute probability estimates of success are available for each subtask then we can estimate the success probability of the entire task (see Figure 7).

Example Task, Goal: Conflict Detection

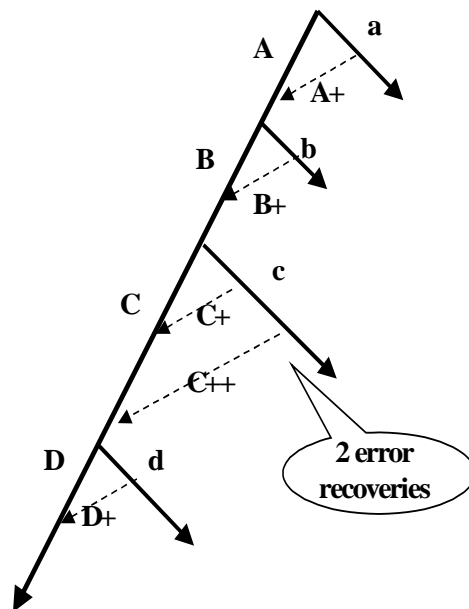
Task A: Monitoring,

Task B: Application of Rules and Procedures

Task C: Decision Making about Conflict, and

Task D: Executing Conflict Resolution Plan

A = Success, a = Failure, A+ = Recovery,



*Dotted line represents error recovered path due to decision support tool or procedural intervention*

**Figure 7. Use of Decision Tree Analysis.**

Figure 8 describes the overall process for the human error assessment.

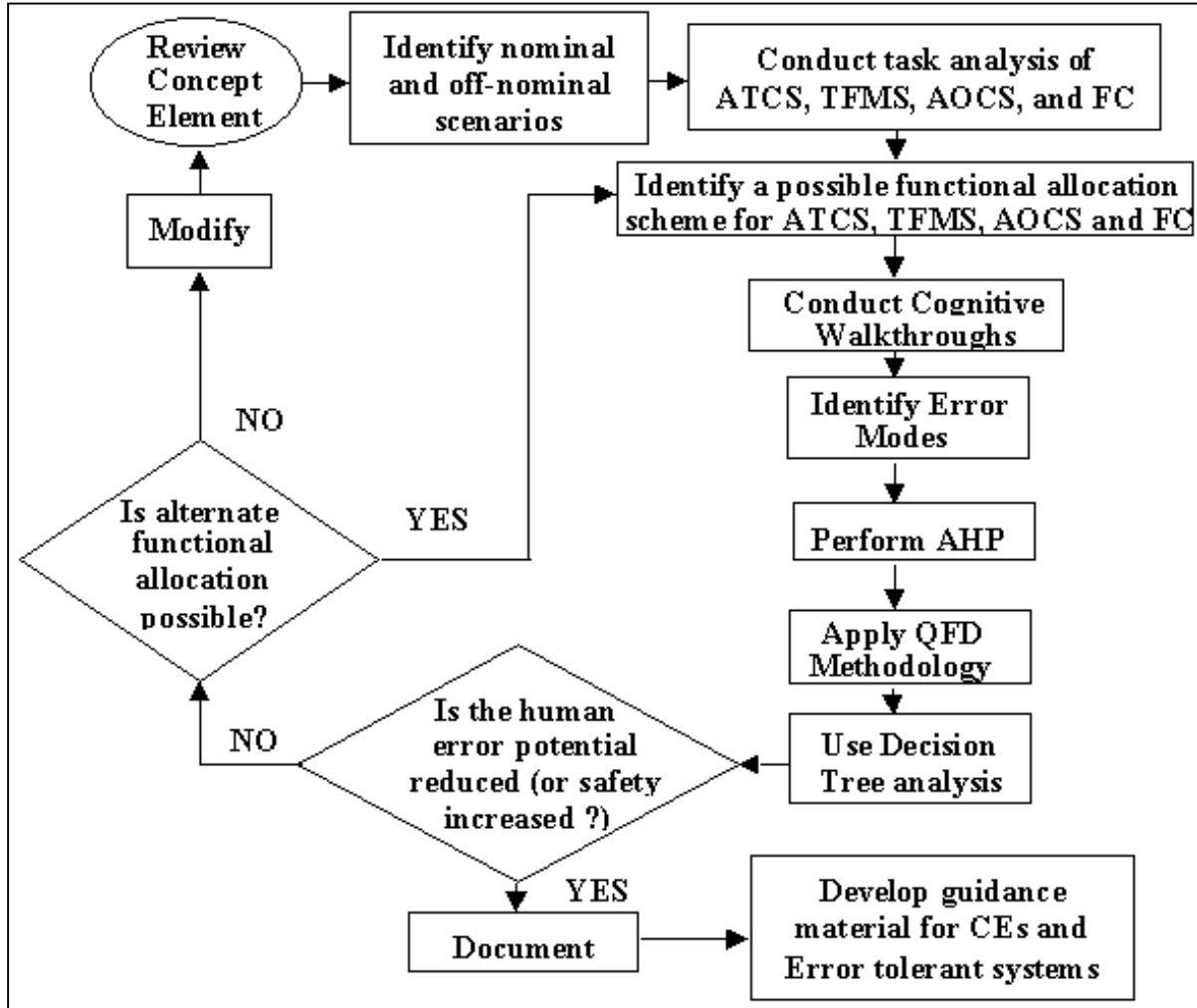


Figure 8. Human Error Assessment Process for DAG-TM.

## 7. CONCLUSION

The prospective human error assessment process described above provides a comprehensive framework to identify errors, trace the system design characteristics to errors, compare alternatives for their error potential, and ensure that critical tasks have redundant error recovery modes.

In addition to following the process, a simulation error databank should be established. Such a databank will record error, its cause, and circumstances (or performance shaping factors). As this databank becomes populated, further information related to error and mitigation strategies can be derived.

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## ACRONYM LIST

AHP	Analytic Hierarchy Process
AOC	Airline Operations Center
AOCS	Airline Operations Center Specialists
ATC	Air Traffic Control
ATSP	Air Traffic Service Provider
ATM	Air Traffic Management
CD&R	Conflict Detection and Resolution
CE	Concept Elements
DAG-TM	Distributed Air-ground Traffic Management
DST	Decision Support Tool
EEM	External Error Modes
FC	Flight Crew
HERA	Human Error Reduction in ATM
IEM	Internal Error Modes
IMC	Instrument Meteorological Conditions
PEM	Psychological Error Modes
SME	Subject Matter Expert
SUA	Special Use Airspace
TFM	Traffic Flow Management
TFMS	Traffic Flow Management Specialist
TRACER	Technique for Retrospective Analysis of Cognitive Errors
VMS	Visual Meteorological Conditions

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## APPENDIX A: HUMAN ERROR ANALYSIS USING ANALYTIC HIERARCHY PROCESS – A SIMPLIFIED HYPOTHETICAL EXAMPLE

The following example is intended to provide an idea about the approach. The example is not meant as a complete analysis mechanism. The level of error analysis will depend on the task, task analysis details, and scenarios.

**Alternative schemes:** Baseline (current operations), CE 5: Trajectory Negotiation (More alternative schemes can be easily considered, but this example uses only two schemes).

**Task:** – Trajectory Negotiation under En Route domain.

**Subtasks:** – Monitoring, Communications, conflict detection.

**Comparison Rating Scale:** modified to suit human error potential comparison.

Human Error Potential	Rating Scale – Numerical Value
Equal	1
Equal to moderately higher	2
Moderately higher	3
Moderately to strongly higher	4
Strongly higher	5
Strongly to very strongly higher	6
Very strongly higher	7
Very strongly to extremely higher	8
Extremely higher	9

### ***Step 1 – Conduct pairwise comparison for each subtask***

The pairwise comparison is performed by an SME (only one SME provides input here, but others may also.) Analysis details vary, but the process is the same. All diagonal cells have a value of 1. In the table below, for the monitoring subtask, the baseline alternative's human error potential is much higher than CE 5.

Subtask: Monitoring		
	Baseline	CE 5
Baseline	1	5
CE 5	1/5	1

Similarly, conduct pairwise comparison for communications, and conflict detection. Assume that the following values are generated.

Subtask: Communications		
	Baseline	CE 5
Baseline	1	3
CE 5	1/3	1

Subtask: Conflict Detection		
	Baseline	CE 5
Baseline	1	7
CE 5	1/7	1

### **Step 2: Compute Normalized Matrix with Row Averages**

First, compute column totals for each subtask.

Subtask: Monitoring		
	Baseline	CE 5
Baseline	1	5
CE 5	1/5	1
Column Total	1.2	6

Subtask: Communications		
	Baseline	CE 5
Baseline	1	3
CE 5	1/3	1
Column Total	1.33	4

Subtask: Conflict Detection		
	Baseline	CE 5
Baseline	1	7
CE 5	1/7	1
Column Total	1.14	8

Second, divide each cell by column total for each subtask.

Subtask: Monitoring			
	Baseline	CE 5	Row Average
Baseline	$1/1.2 = 0.83$	$5/6 = 0.83$	0.83
CE 5	$0.2/1.2 = 0.17$	$1/6 = 0.17$	0.17
Column Total	1.2	6	1

Subtask: Communications			
	Baseline	CE 5	Row Average
Baseline	$1/1.33 = 0.75$	$\frac{3}{4} = 0.75$	0.75
CE 5	$0.33/1.33 = 0.25$	$\frac{1}{4} = 0.25$	0.25
Column Total	1.33	4	1

Subtask: Conflict Detection			
	Baseline	CE 5	Row Average
Baseline	$1/1.14 = 0.88$	$7/8 = 0.88$	0.88
CE 5	$0.14 = 0.1228$	$1/8 = 0.12$	0.12
Column Total	1.14	8	1

Third, record preference vector for each subtask (row averages computed above).

Monitoring	Row Average
Baseline	0.83
CE 5	0.17
Column Total	1

Communications	Row Average
Baseline	0.75
CE 5	0.25
Column Total	1

Conflict Detection	Row Average
Baseline	0.88
CE 5	0.12
Column Total	1

Finally, record a subtask preference vector.

	Monitoring	Communications	Conflict Detection
Baseline	0.83	0.75	0.88
CE 5	0.17	0.25	0.12

### Step 3: Ranking the Criteria

In this step, relative importance of each subtask is computed from most important to the least important in terms of their impact on severity of errors.

	Monitoring	Communications	Conflict Detection
Monitoring	1	4	$\frac{1}{2}$
Communications	$\frac{1}{4}$	1	$\frac{1}{5}$
Conflict Detection	2	5	1

Then, compute the column sum.

	Monitoring	Communications	Conflict Detection
Monitoring	1	4	$\frac{1}{2}$
Communications	$\frac{1}{4}$	1	$\frac{1}{5}$
Conflict Detection	2	5	1
Column sum	3.25	10	1.7

Then, divide each cell by its column sum.

	Monitoring	Communications	Conflict Detection
Monitoring	$1/3.25 = 0.31$	$4/10 = 0.4$	$0.5/1.7 = 0.29$
Communications	$0.25/3.25 = 0.0769$	$1/10 = 0.1$	$0.2/1.7 = 0.12$
Conflict Detection	$2/3.25 = 0.62$	$5/10 = 0.5$	$1/1.7 = 0.59$
Column sum	3.25	10	1.7

Then, compute row averages to give a preference vector.

	Monitoring	Communications	Conflict Detection	Row Averages
Monitoring	$1/3.25 = 0.31$	$4/10 = 0.4$	$0.5/1.7 = 0.29$	0.33
Communications	$0.25/3.25 = 0.0769$	$1/10 = 0.1$	$0.2/1.7 = 0.12$	0.099
Conflict Detection	$2/3.25 = 0.62$	$5/10 = 0.5$	$1/1.7 = 0.59$	0.57
Column sum	3.25	10	1.7	1.0

#### **Step 4: Developing an overall ranking**

Develop an overall ranking by multiplying criteria preference vector and subtask preference vector.

	Row averages
Monitoring	0.33
Communications	0.099
Conflict Detection	0.57

	Monitoring	Communications	Conflict Detection
Baseline	0.83	0.75	0.88
CE 5	0.17	0.25	0.12

**Overall ranking for Baseline** =  $0.33 \times 0.83 + 0.099 \times 0.75 + 0.57 \times 0.88 = \mathbf{0.84975}$

**Overall ranking for CE 5** =  $0.33 \times 0.17 + 0.099 \times 0.25 + 0.57 \times 0.12 = \mathbf{0.14925}$

As seen by the overall ranking, the baseline has a higher human error potential as compared with the CE 5. Therefore, CE 5 is selected strictly based on human error potential and the subtasks that were considered. For details of AHP process, analysis methods, and other details, the reader may refer to *Multicriteria Decision Making: The Analytic Hierarchy Process* (Saaty, 1996).

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